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TECHNOLOGY IDENTIFICATION, EVALUATION, AND SELECTION FOR COMMERCIAL TRANSPORT AIRCRAFT

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ABSTRACT

This paper outlines a comprehensive, structured, and robust methodology for decision making in the early phases of aircraft design. The proposed approach is referred to as the Technology Identification, Evaluation, and Selection (TIES) method. The nine-step process provides the decision maker/designer with an ability to easily assess and trade-off the impact of various technologies in the absence of sophisticated, time-consuming mathematical formulations for project resource allocation. The method also provides a framework where *technically feasible and economically viable alternatives* can be identified with accuracy and speed while the impact on the economics is quantified. Furthermore, structured and systematic techniques are utilized to identify possible concepts and evaluation criteria by which comparisons could be made. Through the implementation of each step, the best family of alternatives for a customer-focused overall measure of value can be identified and assessed subjectively or objectively. This method was applied to a 150 passenger, intra-continental commercial transport as a proof of concept investigation.

MOTIVATION

The design of complex systems, such as commercial aircraft, has shifted its focus from the traditional design for performance to design for affordability. This paradigm shift calls for solutions outside of the traditional, historical evolutionary databases and demands the consideration of all life cycle associated implications [1]. The shift implies a new means of evaluating the "goodness" of an aircraft system must be established in lieu of the standard system level metrics, such as minimum gross weight or maximum performance. In the most general sense, this can be established with a customer focused "Overall Measure of Value" for the system under consideration. The Overall Measure of Value (OMV) is established based on defined customer needs or wants of a system. The customer need not be a cohesive entity, such as an airline, but can be more abstract, such as a response to a societal need or military threat. In that case, the system of interest for which the OMV is defined is the vehicle. Else, if the customer is the designer, the system can be a sub-component of the vehicle.

One method of decomposing the OMV into contributing elements is shown in Figure 1. For some societal need, the OMV elements may include definitive and "fuzzy" requirements. The definitive requirements constitute quantitative measures (approach speed), while the "fuzzy" requirements are qualitative measures (passenger comfort). The arrows going from the "fuzzy" to the definitive measures imply that information between these two elements can be transferred. Information transfer occurs when an ambiguous (qualitative) want of the customer (seat comfort) is translated into a quantifiable engineering parameter (seat pitch or width). As the design cycle progresses, knowledge about the design increases, the ambiguity diminishes, and the customer "wants" become more defined. Hence, the "fuzzy" nature of the requirements are mapped to definitive measures.

The definitive requirements are further delineated into constraints and objectives. The constraints are rigid limits placed on the system and may be either implicit or explicit. The implicit constraints are driven by compliance with the laws of physics and are not negotiable (i.e., must be satisfied). On the other hand, the explicit constraints are clear, expressed limits as defined by the customer. The explicit constraints are rigid limits but are negotiable in the context of the OMV structure. The objectives are figures of merit that characterize a system. The objectives are not constrained but do have an associated target or goal (maximize, minimize, or nominal values). As in the case of information flow from the "fuzzy" to definitive requirements, constraints and objectives can be interchangeable. An explicit constraint could be relaxed to an objective if the designer could negotiate with the customer to determine a compromised requirement.

The focus of the current investigation is to describe a robust method whereby the OMV can be evaluated. In this investigation, the OMV is defined in terms of technical feasibility and economic viability. A method is needed since the customer requirements ("fuzzy" and definitive) for future aircraft concepts are pushing the limits of present day technologies to meet the drastically improvements desired over current system figures of merit. This goal can only be achieved through subsystem improvements with advanced technology concepts. Hence, a question is posed:

> *What is the optimal mix of technologies which will maximize the overall measure of value (i.e., feasibility and viability) of a future system?*

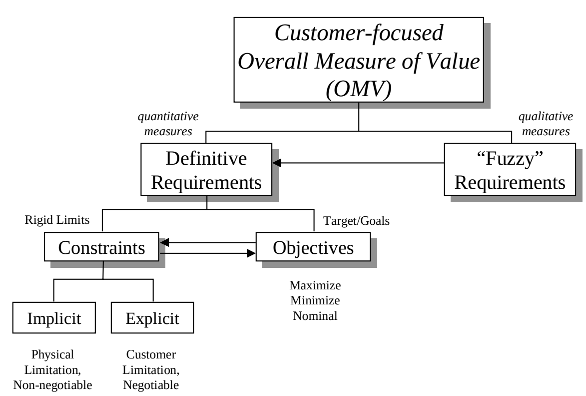

FIGURE 1: OVERALL MEASURE OF VALUE

A method proposed by the authors will address the solution to this question. The method to be described is an expansion of the Technology Identification, Evaluation, and Selection method originally described in Reference [2]. The process utilizes various techniques developed in other technical, operational, and mathematical fields and include Response Surface Methods [3,4,5], Robust Design Simulation [5,6,7], use of a Morphological Matrix [8], a Pugh Evaluation Matrix [9], and Multi-Attribute Decision Making [10].

METHODOLOGY

The methodology developed to address the assessment of the customer focused OMV is depicted in Figure 2. The goal of this method is to provide a framework where technically feasible and economically viable alternatives can be identified with accuracy and speed so as to maximize the customer focused OMV. This method is called the Technology Identification, Evaluation, and Selection (TIES) method and contains nine steps for implementation. These steps are:

1. Problem definition
2. Baseline and alternative concepts identification
3. Modeling and simulation
4. Design space exploration
5. Determination of system feasibility/viability: probability of success
6. Technology identification
7. Technology evaluation
8. Population of the Pugh evaluation matrix
9. Technology selection

PROBLEM DEFINITION (STEP 1)

The first step in the TIES process is to define the problem in question. In order to formulate the problem, a customer or societal need must exist or a request for proposal must be issued to drive the design of a new product. This need is often termed the “voice of the customer” (or “fuzzy” requirements) and is typically qualitative, or ambiguous, in nature. For example, a commercial airline performs a market study and identifies that a majority of potential passengers wish to have lower fares and more flight time options. These are subjective and “fuzzy” requirements that must be mapped into some economic, engineering, or mathematically quantifiable terminology (i.e., definitive requirements). A very efficient method for this mapping is the Quality Function Deployment method [11]. With this mapping, the OMV may be quantitatively assessed. For a commercial system, the quantitative OMV elements of interest (i.e., system metrics) must capture the needs and wants of the customers: airframe manufacturer, airlines, airports, passengers, and society as a whole through operational/environmental regulations.

The system metrics can be mapped into system (product and process) characteristics, or attributes. Primary product characteristics include the physical design parameters that describe the state of a system (e.g., wing area, engine fan pressure ratio). In the conceptual design phase, all of these parameters are not fixed but can vary, and thus be traded off, within some specified range until a configuration is “frozen”. The process characteristics include manufacturing, economic, and operational parameters (e.g., production learning curves, passenger load factors, fuel cost) which are inherently uncertain.

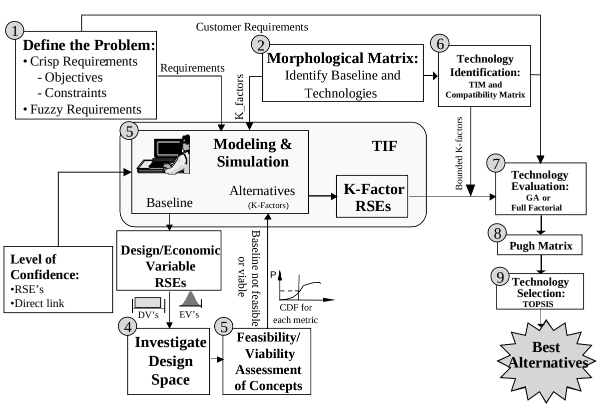

FIGURE 2: TECHNOLOGY IDENTIFICATION, EVALUATION, AND SELECTION METHOD

BASELINE AND ALTERNATIVE CONCEPTS IDENTIFICATION (STEP 2)

In the conceptual stage of aircraft, there exists a plethora of combinations of particular subsystems or attributes that may satisfy the customer needs: how many engines are needed? What is the cruise speed? What type of high lift system is needed? A functional and structured means of decomposing the system is through the use of a Morphological Matrix [8]. This matrix aids the decision maker/designer in identifying possible new combinations of subsystems to meet the customer driven OMV. An example Morphological Matrix is depicted in Figure 3 for a pen. The circled items denote the combination of various attributes (i.e., characteristics which describe the system) of which comprise a single concept. For example, the circled characteristics define a ball point pen which has a metal casing and writes a medium black line. In the context of the TIES method, a conventional configuration (one which contains present day technologies) is chosen as a datum point to begin the technical feasibility investigation. Other combinations of attributes constitute the alternatives. No limit should be placed on the number of alternatives, nor should the alternatives exclude exotic ideas. The Morphological Matrix is a tool for which ideas and creativity are preferred.

Characteristics	Alternatives		
	1	2	3
Casing	Plastic	Metal	Hybrid
Writing Tip	Felt	Ball	
Color	Black	Red	Blue
Line Width	Fine	Medium	Heavy

FIGURE 3: EXAMPLE MORPHOLOGICAL MATRIX

MODELING AND SIMULATION (STEP 3)

A modeling and simulation environment is needed to assess the system metrics which contribute to the OMV for the concepts identified from the Morphological Matrix. In the conceptual stages of aircraft design, a rapid assessment is desired so that trade-offs can be performed with minimal time and monetary expenditures. These trade-offs are typically performed in a monolithic or legacy vehicle sizing and synthesis code. A vehicle sizing/synthesis code is a multi-disciplinary tool (aerodynamics, structures, etc.) Yet, the level of each disciplinary area is based on historical data for evolutionary concepts. If the designs of interest fall within this range, the sizing/synthesis code can accurately assess the metrics. However, for a non-conventional concept, the level of confidence of the results will be questionable. The questionable results can be overcome through direct linking of more physics-based analytical models, or through the use of metamodels to represent the physics-based analysis tool [12] and thus replace a given discipline deficiency. This process yields a preliminary design, vehicle specific sizing and synthesis tool. For brevity, the reader is directed to Reference [1] for a more detailed description of this step and Reference [2] for an implementation example.

DESIGN SPACE EXPLORATION (STEP 4)

The design space exploration begins with the establishment of datum values for all metrics of interest via an alternative concept modeling in a synthesis/sizing tool. The design space (represented by the design parameter variation) of a conventional configuration is initially investigated and datum values quantified. Similar to the aircraft attribute alternatives of the Morphological Matrix, there exists an infinite number of design variable combinations or settings in the early phases of design. There are three methods by which this space can be investigated for feasible/viable solutions: 1) linkage of an actual simulation code with a Monte Carlo simulation; 2) creation of a Metamodel and linkage to a Monte Carlo model; and 3) Fast Probability Integration (FPI) [13,14]. Due to uncertainty in the design process, each of the methods are probabilistic in nature rather than deterministic. The end result of each method is a cumulative distribution function (CDF) for each metric. The first method is the most accurate and most computationally intense since the analysis tool is executed directly. Typically, ten thousand random simulations must be executed for a reasonable CDF. The second method uses a particular metamodel called a Response Surface Equation (RSE) to approximate the analysis tool and a Monte Carlo simulation is performed on this equation. This method has been applied for various investigations [5,6,7,12] and is limited to a maximum of sixteen variables for a second-order approximation. The third method, FPI, approximates the CDF of the metrics directly using the analysis tool with fewer code executions. This technique is very efficient and accurate and has been applied in References [13,14]. It is the designer's discretion as to which method is most suitable.

DETERMINATION OF SYSTEM FEASIBILITY/VIABILITY: PROBABILITY OF SUCCESS (STEP 5)

The evaluation of concept feasibility/viability is based on the probability value of a given metric for the specified target value on the CDF. For example, if a metric has an 80% confidence of achieving the target, the design space available for optimization or deviation is plentiful. Yet, a low probability value (or small confidence) of achieving a solution that satisfies the constraints/goals implies that little room exists for geometric or disciplinary optimization and a means of improvement must be identified. This includes, but is not limited to, the infusion of new or alternative technologies. The need for the infusion of a technology is required when the manipulation of the variable ranges has been exhausted, optimization is ineffective, constraints are relaxed to an extremal limit, and the maximum performance attainable from a given level of technology is achieved. When this limit is reached, there is *no other alternative* but to infuse a new technology to satisfy the OMV.

Unfortunately, advanced technologies are difficult to assess. As mentioned earlier, sizing/synthesis tools are based on regressed historical data that limits or removes the applicability to exotic or revolutionary concepts or technologies. However, the impact of a technology can be qualitatively assessed through the use of technology metric "k" factors. These "k" factors modify disciplinary technical metrics, such as specific fuel consumption or cruise drag, which are calculated within a synthesis tool as a vehicle is sized. The modification is essentially a change in the technical metric, either enhancement or degradation as the vehicle mission is simulated. In effect, the "k" factors mimic the discontinuity in benefits and/or penalties associated with the infusion of a new technology.

In the conceptual stage of a design cycle, the designer wants insight as to which discipline(s) can most affect the probability of success of vehicle's feasibility and viability. Once these disciplines are identified, program funds may be directed to those areas for technology development and application. To facilitate this program resource allocation, disciplinary technical metrics must be identified and appropriate ranges established. The ranges must capture potential benefits *and* penalties to the entire vehicle. The analysis can be performed via a Design of Experiments [3] and visualized with the prediction profile feature of the JMP statistical package [15], such as the example depicted in Figure 4. The technology in this example is focused on the aerodynamic discipline metric, the L/D ratio. One can assume that the L/D can be improved by some *generic* technique, say laminar flow control. This technology supplies not only benefit, but a penalty or degradation in the system. For laminar flow control, this penalty comes through increased SFC and reduced utilization where the “-1” and “1” corresponds to a normalized range for the “k” factors shown. The SFC is increased due to engine bleeding and power extraction needed for the suction effect over wing. As the “k” factor increases towards “1”, the benefit of improved L/D increases, yet, the penalty of the increasing SFC (towards “-1”) reduces the benefits. Utilization is also affected through increased maintenance efforts and higher maintenance man hours per flight hour.

Yet, if a “k” factor for a given technological metric is shown to improve the system metrics with minimal penalties, that technology impact can be identified as worthy of further investigation. An actual technology must be identified which can provide the “k” factor projections. This method is essentially forecasting the impact of a technology. This technique provides a very efficient means of identifying design alternatives around concept “show-stoppers” in an interactive environment for the designer. Hence, optimal resource allocation can be directed to the appropriate disciplinary areas for technology research and development.

$$\mathrm{OBJ} = \left[k_{m_1}(\mathrm{benefit}_1) + k_{m_2}(\mathrm{benefit}_2) + \ldots\right] + \left[k_{m_1}(\mathrm{penalty}_1) + k_{m_2}(\mathrm{penalty}_2) + \ldots\right]$$

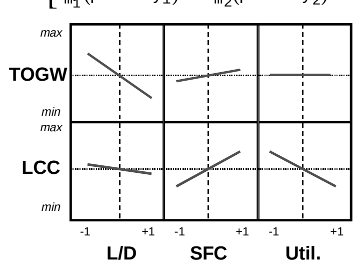

FIGURE 4: EXAMPLE “K” FACTOR PREDICTION PROFILE

TECHNOLOGY IDENTIFICATION (STEP 6)

If the feasibility and viability assessments in step 5 yield an unacceptable probability of success, specific technologies must be identified for infusion which could possibly provide the needed technical “k” factor projections. From the Morphological Matrix in step 2, applicable technologies or technology programs for the class of vehicle under consideration must be identified. The designer or decision maker must establish physical compatibility rules and quantitative impacts to the system to facilitate the identification of the “best” mix of technologies to maximize the OMV.

Compatibility Matrix

A compatibility matrix is formalized through Integrated Product Teams to establish physical compatibility rules between technologies. An example matrix is shown in Figure 5 for three arbitrary technologies (T1,T2,T3) where a “1” implies compatibility and a “0” implies incompatibility. It should be noted that the limiting case of compatibility is a combination of two technologies. Hence, the matrix is two-dimensional and symmetric. In this matrix, T1 and T2 are not compatible. An example of which would be Hybrid Laminar Flow Control (HLFC) and a composite wing structure. The purpose of this matrix is to eliminate combinations that are not physically realizable and reduces the computational requirements of the alternatives to be evaluated.

Compatibility Matrix (1: compatible, 0: incompatible)	T1	T2	T3
T1	1	0	1
T2		1	0
T3			1

FIGURE 5: EXAMPLE TECHNOLOGY COMPATIBILITY MATRIX

Technology Impact Matrix

Once the compatibility matrix is determined, the potential system and sub-system level impact of each technology is established and must include primary benefits and secondary degradations. In general, the impact of a technology is probabilistic in nature, even possibly stochastic. The probabilistic nature arises from various contributing factors. If the technology to be applied has not matured to the point of full-scale application, the primary impact on the system is not certain and must be estimated. The impact estimation comes from three sources: expert team questionnaires, physics-based modeling, or literature reviews.

Each source of impact estimation has an associated uncertainty. In some cases, this uncertainty is not quantifiable. For example, if one was to ask an aerodynamics expert how much drag reduction would result from the addition of HLFC to a vehicle, the answer would be subjective and based on experience and knowledge of that expert with HLFC. Furthermore, the expert’s estimate may be based on a disciplinarian's point of view without knowledge of other discipline limits unless iterative schemes of information flow between experts exists. This iterative scheme is costly and time consuming and decisions and information are usually lost. Next, uncertainty is also associated with estimates stemming from physics-based modeling. This arises from the fidelity of the analysis tool utilized (panel code versus 2nd order Navier-Stokes CFD code), geometry modeling (flat plate versus full three-dimensional), and the assumptions around the analysis (point mass flight simulator versus six degree of freedom model). Finally, if a literature review is the only means of quantifying the impact of a technology, the issue of applicability across classes of vehicles is posed. If a technology has matured on one system, can one apply the same impact to another, different type of system? Furthermore, if the literature review is of an immature technology, the two previous issues apply.

A primary, underlying theme associated with each source of impact uncertainty is the maturation level of the technology. This aspect introduces the time element, hence a stochastic nature. Typically, the maturity of a technology is qualitatively defined with a Technology Readiness Level (TRL) scale. Throughout the aerospace industry, the definition of this scale varies but is usually mapped into a quantitative scale between "0" and "9". In Table I, a typical definition of the associated "readiness" of a technology, i.e., the maturity level, is listed as reproduced from References [16,17]. One could map this scale into a probabilistic space whereby the TRL is represented by a distribution of a given technology impact. An example is shown in Figure 6. Suppose that an arbitrary technology can provide an estimated Δ% improvement in a disciplinary metric over present day technology. At a given point in a technology development cycle, say TRL=1, the likelihood (or confidence) of achieving the desired Δ% improvement is low as represented by the frequency distribution. This implies that the application of that technology would be a risky endeavor for a company since the desired impact has a high probability of *not* being achieved. Yet over time, if money, manpower, and resources are devoted to the development of the technology, more knowledge and information is gained as to the actual impact to the system and the TRL increases. Hence, the distribution mean shifts and the variability associated with achieving the desired improvement reduces. Therefore, the confidence of attaining the desired impact increases and application to the vehicle concept is more likely. It should be noted that the total area under the distribution remains constant, but the emphasis shifts towards the new technology. In essence, the confidence to achieve the desired technology impact increases and the present technology benefit de-emphasized.

TABLE I: TYPICAL TECHNOLOGY READINESS LEVELS

Level	Readiness Description
0	No concept formulation or only basic ideas
1	Basic principles observed and reported
2	Technology concept and/or application formulated (candidate selected)
3	Analytical and experimental critical function or characteristic proof of concept or completed design
4	Component and/or application formulated
5	Component (or breadboard) verification in a relevant environment
6	System/subsystem (configuration) model or prototype demonstrated/validated in relevant environment
7	System prototype demonstrated in flight
8	Actual system completed and flight qualified through test and demonstration
9	Actual system flight proven on operational flight

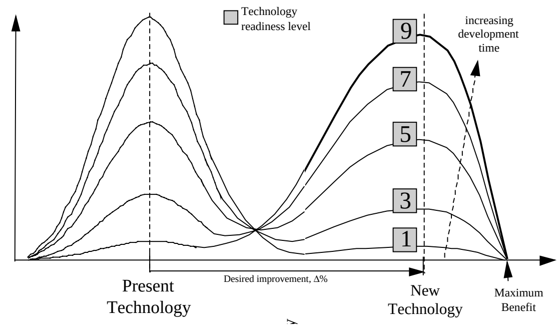

FIGURE 6: EXAMPLE TRL VARIATION WITH TIME

Based on the probabilistic nature described above, a technology impact matrix (TIM) may be formed for the technologies identified. Essentially, the impact of a technology is mapped to a technical "k" factor vector (represented by the elements of a given technology column). Each element of the vector has a mean, variance, and TRL. Not all technologies will affect each element of the vector, but the vector must capture all technologies. An example matrix is shown in Figure 7 for three technologies which influence four technical metrics. In the deterministic example in Figure 7, T1 and T3 affect all "k" factors except for the second, while T2 does not affect the first or third. Each element of the vector is established via the three sources of impact estimation as described previously. The vector *must* include benefits *and* penalties to accurately assess the impact of technologies on the OMV.

	Technical "K" Factor Vector	T1	T2	T3
"K" Factor Elements	k factor 1	+4%	~	-10%
	k factor 2	~	-3%	~
	k factor 3	-1%	~	-2%
	k factor 4	-2%	-2%	+3%

FIGURE 7: EXAMPLE TECHNOLOGY IMPACT MATRIX

TECHNOLOGY EVALUATION (STEP 7)

The technologies identified in step 6 must now be applied to the vehicle concept and evaluated. The evaluation will provide data and information of the system metrics whereby selection of the proper mix may be performed. Yet, the search for the proper mix which will maximize the OMV is dominated by the "curse of dimensionality". Depending on the number of technologies (n) considered, the combinatorial problem can be enormous (2^n combinations, assuming that all combinations are physically compatible as defined by the compatibility matrix). For nine technologies, 512 combinations would exist. For twenty technologies, more than one million combinations would need to be evaluated. In addition, the technology "k" factor vector which influences a vehicle is probabilistic. Hence, to estimate the impact of the 2^n technology combinations, a CDF would need to be generated for each combination, which further complicates the evaluation. Yet, if the computational expense of the analysis is manageable, a full-factorial probabilistic investigation could ensue resulting in a CDF for each metric and concept. Yet if the computational expense is unmanageable (e.g., a finite element analysis), an alternate method of evaluation is needed to downsize the problem. One of the most efficient variable search strategies for combinatorial optimization is a genetic algorithm approach [18,19]. Reference [18] defines genetic algorithms (GA) as "a class of general-purpose search methods…which can make a remarkable balance between exploration and exploitation of the search (design) space" to find the best family of alternatives. A GA search strategy is based on the Darwinian evolution process of survival of the fittest. The GA approach begins with an initial random set of concepts (called a generation) which are evaluated based on a fitness function. Through crossovers and mutations of the initial generation, new successive generations are created through an evaluation of the fitness function (i.e., OMV). After successive iterations, the GA will converge to a population which best satisfies the OMV [18]. The power of the GA approach is the efficient exploration of a dimensionally enormous design space to arrive at a population solution containing the best family of technology alternatives. Once the combinatorial problem is down-sized, the selection of the proper mix of technologies is facilitated with a Pugh Matrix and MADM techniques.

POPULATION OF THE PUGH EVALUATION MATRIX (STEP 8)

The Pugh Evaluation Matrix [9] is a method where concept formulation and evaluation is performed in an organized manner. The concepts identified in Step 6 form the rows, and the definitive requirements (or important metrics) in Step 1 form the columns (metric

	Metric_1	Metric_2	....	Metric_n
Alternative 1	#	#	....	#
Alternative 2	#	#	....	#
Alternative 3	#	#	....	#
Alternative 2^n	#	#	....	#

FIGURE 8: EXAMPLE PUGH MATRIX

vector) as shown in Figure 8. The elements of the matrix are populated from the results obtained in step 7 for each alternative and metric. Since the metrics are in the form of CDFs, the decision maker has the ability to select a confidence level associated with a given metric. The confidence level is also related to the risk or uncertainty associated with a particular technology and the selection of these levels is purely subjective. The corresponding value of the metric (for a fixed confidence level) is then inserted into the appropriate cell of the matrix. This process is repeated for each metric and concept.

TECHNOLOGY SELECTION (STEP 9)

Once the Pugh Matrix is populated, the next step is to determine the best family of alternative concepts. This decision making process is facilitated through the use of Multiple Attribute Decision Making (MADM) techniques. For the purpose of the TIES methodology, a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is utilized [10]. TOPSIS provides an indisputable preference order of the solutions obtained in the Pugh Matrix with the end result being a ranking of the best alternative concepts.

First, a decision matrix is formed from the Pugh Matrix. If any of the metrics are subjective in nature, an interval scale may be utilized. From this matrix, each element of a metric vector (i.e., a given column) is non-dimensionalized by the Euclidean norm of that metric vector. If so desired, subjective weights may be placed on each metric to establish a relative importance. Next, each metric vector must be classified as a "benefit" or a "cost" whereby a maximum of a benefit and a minimum of a cost are desired. Positive and negative ideal solution vectors are then established. The positive vector elements consist of the maximum value of the "benefit" metrics and the minimum value of the "cost" metrics. The negative vector is the compliment of the positive vector. Next, the distance of each alternative from the positive and negative ideal solution is measured by the n-dimensional Euclidean distance, where "n" is the number of alternatives. Finally, each alternative is ranked from "best" to "worst" based on the closeness to the positive solution and distance from the negative ideal solution. These rankings can change depending upon the level of confidence and metric weightings assumed.

Finally, the robustness of the best alternatives can be evaluated with various techniques. One method is the

Robust Design Simulation which has been implemented for various vehicle concepts. The reader is referred to References [20,21,22] for more information. Additionally, the "best alternative(s)" should be re-investigated with regards to the design variable settings, i.e., Steps 3 through 5 are repeated.

IMPLEMENTATION

The TIES method described above was applied to an intra-continental, medium-range, commercial transport. For brevity, the new aspects of TIES from Reference [2] are emphasized while the repeated elements from Reference [23] are de-emphasized.

PROBLEM DEFINITION (STEP 1)

The first step in any design method is to define the problem. Herein, the problem statement was driven by societal commercial needs due to the forecasted growth in travel. Commercial world air travel is expected to grow at a rate of 5.5% per year over the next decade [24], resulting in a 71% increase from current levels within a decade and increasing 192% in two decades. These projections have spawned interest in various commercial vehicle concepts to respond to the predicted growth, including a long-range, high capacity transport and a medium-range, intra-continental transport. For this study, the latter concept was the class of vehicle to be investigated.

Once the societal need was established, the customer "wants" must be mapped into some engineering or quantifiable terminology, i.e. system metrics, so as to evaluate the OMV. The metrics for this study were economic- and performance-based and include Direct Operating Costs per trip plus Interest (DOC+I), Total Airplane Related Operating Costs (TAROC), approach speed (Vapp), fuel burn or weight, landing field length, operating empty weight (OEW), takeoff field length (TOFL), and takeoff gross weight (TOGW). The two economic parameters, DOC+I and TAROC, have recently become important metrics for measuring commercial transport affordability. DOC+I constitutes 55% of the passenger ticket price and includes: flight and cabin crew salaries, engine and airframe maintenance, fuel and APU costs, insurance, depreciation, interest, and landing fees. TAROC is the DOC+I plus ground handling, property, maintenance, and depreciation; and general and administrative costs, and is an additional 10% of the passenger ticket price.

Target values for these metrics were a percent reduction from present day predictions: –42% DOC+I, –37% TAROC, –48% fuel weight, –21% landing field length, –40% OEW, –21% TOFL, and –31% TOGW. Vapp was to be minimized with no associated target. All metrics were classified in the OMV structure as objectives since no rigid limits were imposed only targets or goals.

BASELINE AND ALTERNATIVE CONCEPTS IDENTIFICATION (STEP 2)

The vehicle for this study was decomposed into sub-components, and through brainstorming activities and literature reviews, various alternatives were associated with each characteristic or system attribute. The Morphological Matrix utilized in this investigation is shown in Figure 9. As stated previously, a datum point must be established from this matrix. This datum was assumed to be the combination of alternatives that represent conventional technologies and consists of the circled characteristics in Figure 9. Combinations of any of the other characteristics constituted concept alternatives.

MODELING AND SIMULATION (STEP 3)

A baseline configuration (or datum point) was established for a 3,000 nm mission with the cruise at a maximum altitude of 35,000 ft at Mach 0.83. The baseline aircraft attributes for this study were similar to a Boeing 737-800. The payload of the aircraft was assumed to be 150 passengers plus baggage, flight crew of two, four flight attendants, two wing-mounted engines, and a fuselage length and diameter of 117.8 ft and 12.58 ft, respectively. Furthermore, to obtain the datum points for viability, primary economic assumptions were established (Table II) which were used for the remainder of this study. A production learning curve (LC) was assumed for two lots. All aircraft sizing and analysis tasks for this study utilized the Flight Optimization System, FLOPS [25]. FLOPS was linked to the Aircraft Life Cycle Cost Analysis, ALCCA, program used for the prediction of all life-cycle costs associated with commercial aircraft [26]. Based on the above system attributes, baseline metric values were established through a sizing and economic analysis of the vehicle in FLOPS/ALCCA. As a result, quantitative values of the percent reduction in metrics were established and are listed in Table III.

	Alternatives / Characteristics	1	2	3	4
Config	Vehicle	Wing & Tail	Wing & Canard	Wing, Tail & Canard	Wing
	Fuselage	Cylindrical	Oval	None	
	Pilot Visibility	Synthetic Vision	Conventional		
Mission	Range (nmi)	3000	3500	4000	
	Passengers	100	150	200	
	Mach Number	0.8	0.83	0.85	0.9
Prop	Type	Turbofan	AST Engine	IHPTET	
	Combustor	Conventional	RQL	LPP	
Control	Static Stability	Stable	Unstable	Relaxed	
	Gust control	Conventional	Unloaded		
Aero	Low Speed	Conventional Flaps	Conventional Flaps & Slots	C C	
	High Speed	Conventional	LFC	NLFC	HLFC
Struct	Wing	Aluminum	Titanium	Composite	
	Fuselage	Aluminum	Titanium	Composite	

FIGURE 9: CONCEPT MORPHOLOGICAL MATRIX

TABLE II: ECONOMIC ASSUMPTIONS

Parameter	Value	Parameter	Value
Airframe LC for 1st lot	81.5%	Engineering Labor Rate	$89.68/hr
Airframe LC for 2nd lot	85.0%	Financing Period	20 yrs
Airframe Spares Factor (of airframe price)	6%	Fiscal Year Dollars	1996
Airline ROI	10%	Fixed Eq. LC for 1st lot	82.0%
Assembly LC for 1st lot	76.0%	Fixed Eq. LC for 2nd lot	85.0%
Assembly LC for 2nd lot	79.0%	Fuel Cost	$0.70/gal
Average Annual Inflation	8.00%	Hull Insurance Rate (of aircraft price)	0.35%
Avionics LC for 1st lot	81.5%	Load Factor	65%
Avionics LC for 2nd lot	85.0%	Maintenance Burden Rate (of direct labor)	200%
Depreciation Residual Value (price including spares)	10%	Maintenance Labor Rate	$25.00/hr
Downpayment	0%	Manufacturer ROI	9.2%
Economic Life	20 yrs	Production Quantity	640 units
Economic Range	1000 nm	Tooling Labor Rate	$54.68/hr
Engine Spares Factor (of engine price)	6%	Utilization	3250 hrs/yr
Engine Units Produced	2000	Years of Production	15

TABLE III: QUANTITATIVE SYSTEM METRIC TARGETS

Parameter	Baseline Value	Target	Target Value	Units
Weights and Performance				
V_{app}	115.7	*minimize*	~	kts
Fuel Burn	44267	-48%	23019	lbs
Landing FL	4944	-21%	3906	ft
OEW	73850	-40%	44310	lbs
TOFL	5970	-21%	4706	ft
TOGW	149618	-31%	103236	lbs
Economics				
DOC+I	5.22	-42%	3.03	¢/ASM
TAROC	6.03	-37%	3.80	¢/ASM

DESIGN SPACE EXPLORATION (STEP 4)

The design space exploration for the concept of interest was performed in Reference [23]. The system attributes included design variables with uniform distributions and economic variables with normal distributions. The Advanced Mean Value analysis mode in FPI was utilized to estimate the system metric CDFs. FPI wrapped around FLOPS/ALCCA and controlled the variation of inputs in accordance with the specified attribute distributions and resulted in CDFS for each metric. The reader is referred to Reference [23] for more details.

DETERMINATION OF SYSTEM FEASIBILITY/VIABILITY: PROBABILITY OF SUCCESS (STEP 5)

The CDFs obtained in step 4 displayed the probability of achieving values greater or less than a given target [27]. Each metric CDF was compared to the target values specified in Table III. Of the eight metrics considered, none could meet the specified targets. The probability of success was 0% for all metrics. For brevity, the reader is referred to Reference [23] for more details regarding this step. For the purpose of this investigation, new technologies were infused and the technical feasibility and economic viability was assessed in lieu of geometric optimization or metric target relaxation.

TECHNOLOGY IDENTIFICATION (STEP 6)

Since the probability of success for feasibility and viability was unacceptable in step 5, nine technologies or technology programs were considered for infusion from the Morphological Matrix. The nine technologies were composite wing [28], composite fuselage [28], aircraft morphing [29], natural laminar flow control, maneuver load alleviation [30], NASA's Advanced Subsonic Transport (AST) engine concept [31], integrally stiffened aluminum wing structure [32], HLFC [33,34], and Improved High Pressure Turbine Engine Technology (IHPTET) [35].

Compatibility Matrix

The compatibility rules for these technologies were determined from brainstorming activities and literature reviews and is shown in Figure 10. The technologies listed include specific technologies, such as composite structures for the wing and fuselage, and technology programs, such as aircraft morphing and IHPTET engines. As is evident, some combinations are not physically realizable and will thus reduce the number of alternatives to be evaluated. For example, a composite wing structure could not have HLFC. Due to the manufacturing processes associated with a composite wing, the micro-holes needed for HLFC boundary layer suction would require heavy maintenance costs for panel replacements and create structural integrity problems.

Technology Impact Matrix

The Technology Impact Matrix (TIM) was formed for the nine technologies based on two sources: expert opinions and literature reviews. The TIM for this study was deterministic and the impact of each technology or technology program was obtained from the references cited previously. The deterministic TIM was used as a proof of concept since the ability to efficiently quantify the impact of stochastic technologies has not been developed. This will be the focus of future research.

Compatibility Matrix (1: compatible, 0: incompatible)	Composite Wing T1	Composite Fuselage T2	Aircraft Morphing T3	Natural Laminar Flow Control T4	Maneuver Load Alleviation T5	AST Engine Concept T6	Integrally, Stiffened Aluminum Airframe Structures (wing) T7	HLFC T8	IHPTET Engines T9
Composite Wing	1	1	1	1	1	1	0	0	1
Composite Fuselage		1	1	1	1	1	1	1	1
Aircraft Morphing			1	1	1	1	1	1	1
Natural Laminar Flow Control				1	1	1	1	0	1
Maneuver Load Alleviation					1	1	1	1	1
AST Engine Concept						1	1	1	0
Integrally, Stiffened Aluminum Airframe Structures (wing)		Symmetric Matrix					1	0	1
HLFC								1	1
IHPTET Engines									1

FIGURE 10: CONCEPT COMPATIBILITY MATRIX

The deterministic TIM for the nine technologies is shown in Figure 11. The elements of the technical metric "k" vector are listed on the left and encompass all technology impacts, even though not all technologies contribute to every element. The technical "k" vector was a 15x1 vector and was unique for a given technology. The values shown are conservative estimates from the cited references. The "k" vector included primary benefits and secondary penalties to both performance and economic metrics. For example, the infusion of a composite wing could reduce the sized vehicle wing weight by 15% and the subsonic drag (due to a smoother wing surface) by 2%. Yet, the costs associated with manufacturing and maintaining this type of wing was more than a conventional aluminum wing structure. This secondary penalty was simulated by increased Research, Development, Testing, and Evaluation (RDT&E), production, and Operation and Support (O&S) costs and reduced utilization.

TECHNOLOGY EVALUATION (STEP 7)

The evaluation of the nine technologies identified in step 6 was considered to be computationally manageable since the impact of each technology was deterministic. Hence, a full-factorial investigation was utilized in lieu of a Genetic Algorithm approach. A full-factorial evaluation for nine technologies at two levels (i.e., "on" or "off") constituted 512 ($2^{n=9}$) combinations, but the compatibility matrix reduced that value to 168 combinations. The technology evaluation was performed by creating a metamodel of each system metric in Table III as a function of the "k" vector elements. The metamodels were second-order Response Surface Equations (RSE) of the form:

$$R = b_o + \sum_{i=1}^{k} b_i k_i + \sum_{i=1}^{k} b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} k_i k_j \qquad (1)$$

where: R represents a given system metric; b_i represent regression coefficients for linear terms; b_{ii} quadratic coefficients; b_{ij} cross-product coefficients; k_i, k_j the "k" factor vector elements; and $k_i k_j$ denotes interactions between two "k" vector elements. A metamodel, RSE, was created for each system metric via a Design of Experiments (DoE) by bounding the "k" vector element ranges as defined in Table IV. The "0" implies no change in the technical metric while a negative value denotes a reduction and a positive value an increase. Once Eq (1) was determined for each metric via the statistical package, JMP [15], the RSEs could be used to rapidly evaluate the impact of the various technologies based on a particular "k" vector setting in lieu of executing FLOPS/ALCCA directly.

A full-factorial DoE was created in JMP and the RSEs were evaluated when a compatible mix of technologies existed. As an example, the metric values obtained for a vehicle with aircraft morphing (T3) and IHPTET engines (T9) is depicted in Figure 12. As stated previously, a unique "k" vector was associated with each technology, specifically $\vec{k}_3$ and $\vec{k}_9$. Since the impact of the various technologies was assumed to be additive, an alternative with T3 and T9 was simulated by adding each element of the vector resulting in a new vector, $\vec{k}_{3+9}$. The new vector was then fed into the RSEs and the metrics calculated. This procedure was followed for each of the 168 compatible technology mixes.

Technical K_Factor Vector	Composite Wing T1	Composite Fuselage T2	Aircraft Morphing T3	Natural Laminar Flow Control T4	Maneuver Load Alleviation T5	AST Engine Concept T6	Integrally, Stiffened Aluminum Airframe Structures (wing) T7	HLFC T8	IHPTET Engines T9
Wing area	~	~		~	+18%	~	~	~	~
Vertical tail area	~	~	~	~	-40%	~	~	~	~
Horizontal tail area	~	~	~	~	-36%	~	~	~	~
Drag	-2%	-2%	-3%	-5%	-3%	~	~	-10%	~
Subsonic fuel flow	~	-0.5%	-1.5%	~	~	-10%	~	+1%	-5%
Wing weight	-15%	~	-3%	~	~	~	-15%	+4%	~
Fuselage weight	~	-25%	-2%	~	~	~	~	~	~
Electrical weight	~	~	~	~	+5%	+3%	~	+2%	~
Engine weight	~	~	~	~	~	-30%	~	+0.5%	-20%
Hydraulics weight	~	~	~	~	-10%	~	~	~	~
AL wing structure manufacturing costs	~	~	~	~	~	~	-2.5%	~	~
O&S	+2%	+2%	~	~	~	-3%	-2%	+3%	-3%
RDT&E	+2%	+2%	+2%	+2%	+3%	-4%	~	+4%	+3%
Production costs	+10%	+10%	-3%	+1%	~	-3%	~	+1%	~
Utilization	-2%	-2%	~	~	~	+3%	+2%	-2%	+2%

Technical K_Factor Elements

FIGURE 11: CONCEPT TECHNOLOGY IMPACT MATRIX

TABLE IV: BOUNDED "K" FACTOR ELEMENTS

Technical Metric "K" Factor Elements	Non-dimensional impact Min (%)	Max (%)
Wing area	0	18
Vertical tail area	-40	0
Horizontal tail area	-36	0
Drag	-25	0
Subsonic fuel flow	-17	1
Wing weight	-33	4
Fuselage weight	-27	0
Electrical weight	0	10
Engine weight	-50	0.5
Hydraulics weight	-10	0
AL wing structure manufacturing costs	-2.5	0
O&S	-8	7
RDT&E	-4	18
Production costs	-6	22
Utilization	-6	7

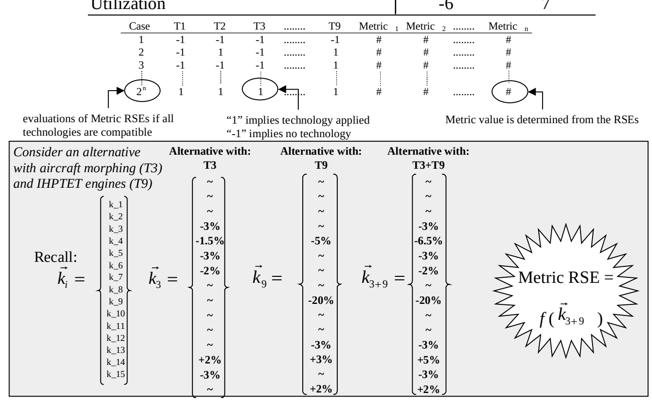

FIGURE 12: EXAMPLE TECHNOLOGY EVALUATION WITH "K" VECTORS

POPULATION OF THE PUGH EVALUATION MATRIX (STEP 8)

The Pugh matrix used in the current investigation was a 168x8 matrix, where there were 168 alternatives and 8 metrics. Since the impact of the technologies was assumed to be deterministic, the actual metric values obtained in step 7 populated the matrix. It should be noted that the most accurate assessment of the technology mixes would be, at the minimum, probabilistic. Hence, the values that would populate the Pugh matrix would be the values associated with a CDF confidence level as determined by the designer or decision maker.

TECHNOLOGY SELECTION (STEP 9)

The selection of the "best" mix of technologies to respond to the customer-focused OMV was facilitated with the TOPSIS method. The Pugh matrix created in Step 8 provided the basis for the TOPSIS decision matrix. The OMV was then formulated based on the performance and economic metrics in Table III and was defined as:

$$\max(OMV) = \alpha \frac{Vapp_{BL}}{Vapp} + \beta \frac{Fuel_{BL}}{Fuel} + \gamma \frac{LdgFL_{BL}}{LdgFL} + \delta \frac{OEW_{BL}}{OEW} + \varepsilon \frac{TOFL_{BL}}{TOFL} + \zeta \frac{TOGW_{BL}}{TOGW} + \eta \frac{TAROC_{BL}}{TAROC} + \theta \frac{DOC+I_{BL}}{DOC+I} \quad (2)$$

The steps executed of the TOPSIS implementation followed those described previously. All metrics were classified as a "cost" since minimization was desired and various subjective weightings were investigated for the coefficient factors in Eq (2), where the sum of the coefficients was one. The subjective weighting influence on the alternative rankings was consistent for the metrics of interest. That is, the alternative rankings were consistent for all performance metrics regardless of weighting values. This trend was also obtained for the economic metrics. Hence, only the "best" alternatives for the OMV as a function of TOGW and TAROC are shown for brevity.

If the OMV was only a function of TOGW (ζ=1), the top ten alternatives that resulted from the TOPSIS analysis are depicted in Figure 13. For legibility, each technology was abbreviated with a T1, T2, etc., and corresponded to the technologies listed in Figure 11. Furthermore, the best alternatives are shown as a percent reduction from the datum point metric values listed in Table III. The technology mix that maximized the reduction of TOGW contained the first six technologies (T1, T2, T3, T4, T5, T6) and reduced the baseline TOGW by 16.7% to 124,500 lbs. The TOGW for this alternative was still 20.3% higher than the target value of 103,236 lbs. in Table III. The second best mix of technologies reduced TOGW by 16.6% and contained T1, T2, T3, T4, and T6. This result implies that the infusion of T5 (maneuver load alleviation) was capable of reducing the TOGW by 0.1%. Even though the empennage weight was drastically reduced, the wing area increase caused the magnitude of TOGW to slightly vary. Yet, the primary reason for applying T5 (i.e., stability issues and load alleviation due to gusts) was not captured by FLOPS/ALCCA. Hence, the TIES method provides a top-level impact assessment of a given technology. The specific physics and detailed dynamics of a system that are associated with the infusion of a technology must be considered concurrently with TIES. The most prominent technologies for reducing TOGW were deduced from the frequency of occurrence from the TOPSIS rankings. As seen in Figure 13, T2, T3, and T6 were the most prevalent technologies and corresponded to composite fuselage, aircraft morhping, and integrally stiffened aluminum wing structure, respectively.

If the OMV was purely a function of TAROC (η=1), the top ten alternatives from TOPSIS differ from those obtained from minimizing TOGW as show in Figure 14. The combination of technologies that minimized TAROC (-15.8%) relative to the datum point was T3, T4, T6, and T7. This combination differed from the above due to the increased RDT&E and production costs associated with T1, T2, and T5. These three technologies supplied a tremendous performance benefit (Figure 13), yet the economic penalties counter-acted the benefits. The most prevalent technologies for reducing TAROC were T3, T6, and T7 (aircraft morhping, AST engine concept, and integrally stiffened aluminum wing structure, respectively). These technologies resulted due to the associated reductions in RDT&E, production costs, etc. while providing performance benefits. Again, none of these alternatives could meet the imposed target reduction of TAROC (-37%). The best alternative was still 32.4% higher than the imposed target.

The combined effect of reducing TOGW and TAROC, i.e., ζ=0.5 and η=0.5, further changed the ranking of the best alternatives (Figure 15). In this case, the

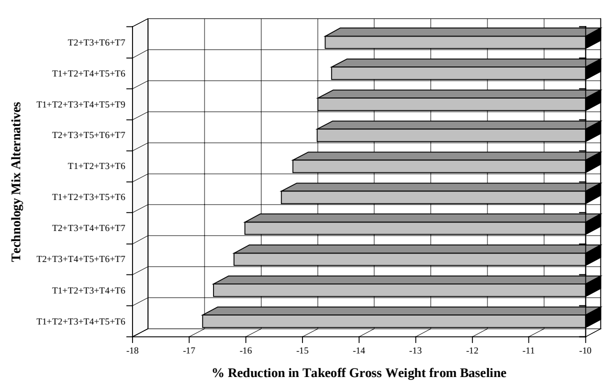

FIGURE 13: BEST ALTERNATIVES FOR MINIMUM TOGW

combination of T2, T3, T4, T6, and T7 maximized the OMV and corresponded to a TOGW reduction of 16.1% and TAROC reduction of 13.1%. Once more, the prevalent technologies for this OMV were T3, T6, and T7 as in the case of the OMV only being a function of TAROC.

Based on all permutations of the OMV weighting factors, none of the technology alternatives considered could meet the imposed metric target reductions in Table III. Hence, by traditional standards, these alternatives would not be classified as technically feasible or economically viable. At this point, the decision maker is presented with two issues. Are the costs to achieve a given percentage change in a system metric significantly outweighed by the costs to achieve that target? And, are the metric target reductions appropriate or could the goals be relaxed. If so, would a technically feasible or economically viable alternative exist? The TIES method provides the decision maker with the ability to address these trade-offs in a rapid and efficient manner. In fact, if the required reductions were 15% for TOGW and 10% for TAROC, a large technically feasible and economically viable space would exist. These decisions are tracked and recorded so that information about the evolution of a design is not lost.

Finally, one aspect of the TIES method was to identify the most influential technologies for resource allocation for technology research and development to overcome constraints or meet objectives. These technologies were identified by a comparison of the infusion of a single technology to the baseline and evaluation of the metric value deviations. T6, T2, and T9 had the most impact in decreasing order. The interesting results arose from the TAROC comparison as shown in Figure 16. As is evident, T6 (AST engine concept) had the most significant impact on TAROC with a -9.2% reduction. Yet, T2 (composite fuselage), which was the second most influential technology for TOGW reduction, was significantly penalizing TAROC and could potentially hurt the economic success of the program. In contrast, the two most prominent technologies for both TOGW and TAROC reductions were technologies associated with propulsion improvements, specifically, an AST engine concept (T6) and an IHPTET engine (T9). This result would imply that the optimal direction for resource allocation in the conceptual phases of design for this class of vehicles would be to the development of enhanced propulsion systems. A secondary focus could be to the integrally stiffened aluminum wing structures (T7). This technology also contributed to the reduction in TOGW of 4.5% and TAROC of 2.4%.

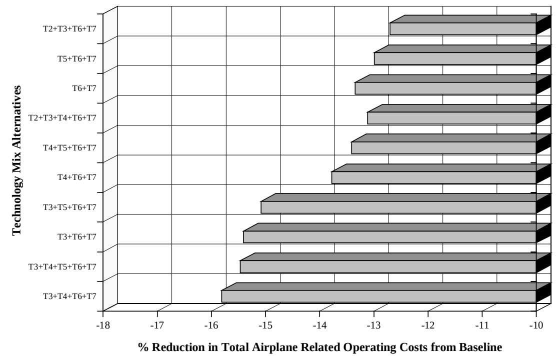

FIGURE 14: BEST ALTERNATIVES FOR MINIMUM TAROC

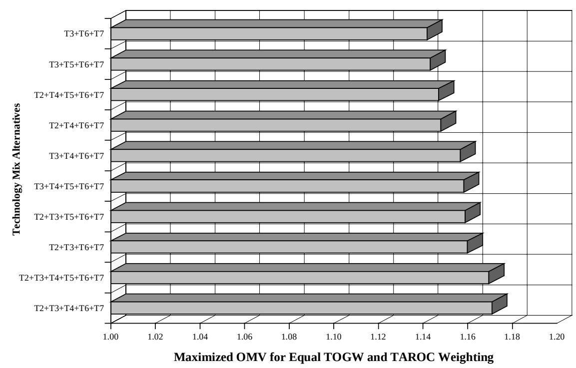

FIGURE 15: BEST ALTERNATIVES FOR MINIMUM TAROC AND TOGW

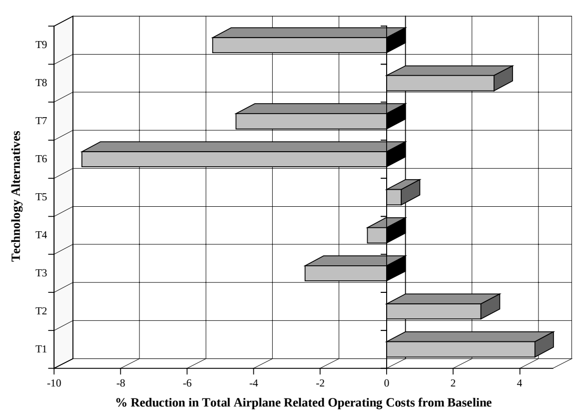

FIGURE 16: INDIVIDUAL TECHNOLOGY IMPACT ON TAROC

CONCLUSIONS

This paper described research in the area of a technology down-select method for future vehicle concepts. A comprehensive, structured, and efficient nine-step method was described which began at the problem definition and proceeded through to the identification of the best alternative(s) in terms of technology mixes for further study. The method is called Technology Identification, Evaluation, and Selection (TIES). Furthermore, the method provided a means by which the designer or decision maker can identify the technologies which most influence performance and economic metrics. Subsequently, resource allocation can be optimally directed for technology research and development to overcome constraints or meet objectives. A proof of concept investigation was performed on a 150 passenger, intra-continental, medium range transport. Based on target values of performance and economic metrics, various technologies were infused to the vehicle concept and the technical feasibility and economic viability assessed. Future target metric values could not be achieved, but potential technologies were identified to improve the system. For the subsonic transport in this study, advances in propulsion technology would most benefit the performance and economic figures of merit.

Future effort in the development of the TIES method will be to extend the method to probabilistic (or stochastic) technology assessments. Also, other means of assessing the combinatorial problem of the technology mixes will be applied, in particular, genetic algorithms.

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